Maintenance priorities determination for a repairable unit of a sugar plant

1Gaurav Sharma and 2P C Tewari
1Department of Mechanical Engineering, NIT Kurukshetra, Haryana
2Department of Mechanical Engineering, NIT Kurukshetra, Haryana
gaurav_6150009@nitkkr.ac.in

Abstract. In the present study, a repairable unit of a sugar plant has been considered to determine the maintenance priorities of various subsystems of the unit. The selected repairable unit is crushing unit and it comprises of crusher, inter carrier and pump subsystems. Performance modeling of the unit is based on Markov approach. From the transition diagram of the unit, Chapman-Kolmogorov differential equations are derived. The equations are then solved to get the availability in steady state. It is assumed that all subsystems have constant rates of failure and repair. After that, development of decision matrices has been done for all subsystems. For various permutations of failure rates as well as repair rates, these decision matrices present different levels of availability for all the subsystems. On the basis of various values of availabilities and the graphs of failure and repair rates of subsystems, the optimum values of failure and repair rates are selected for maximum availability of each subsystem. Accordingly, priorities for maintenance are determined for various subsystems of repairable crushing unit. This will ensure maximum availability level of the crushing unit and will finally lead to the overall performance enhancement thereby maximizing the profitability of the plant.

Keywords: Performance Analysis, Crushing Unit, Maintenance Priorities

1. Introduction
Reliability concept is of great importance at design stage, operation stage and maintenance stage. It has been realized that reliability and availability has immense importance in all the complex processing industries. Availability of any repairable unit generally depends upon the failure and repair rates of the subsystems. For attaining required availability level of a unit, proper design and adequate maintenance of all of its subsystems is must. The improvement in maintenance strategy of a unit is more convenient than modifying the design of that unit. Therefore, in the present paper, stress is given on the necessity of determination of maintenance priorities at a sugar plant. In any process plant, raw material passes through different units for different types of processes. For ensuring the long run availability, all the subsystems of the unit must run failure free for prolonged hours. The failure of any component or subsystem of the unit will slow down the efforts to get long run availability. Performance Analysis in terms of availability helps in obtaining the necessary information related to different parameters of the unit. A lot of work has been done by many researchers in the field of reliability and availability for the systems of various industries. Blake and Trivedi [1] proposed a two-level hierarchical model in which they modeled each subsystem as a Markov chain. The reliability modeling of the system is then done as a series system of independent Markov components. Gupta et
al. [2] developed a Markov model for evaluation of performance of the coal handling unit of a thermal power plant. This performance model helps in comparing alternative strategies for maintenance of the unit. Hokstad et al. [3] presented a time continuous Markov chain model for deterioration and repair of a railway line. The modeling of state change at the end of inspection interval is done as a time discrete Markov chain. Jaffer et al. [4] created the Reliability Block Diagram for compressor unit of utility plant on the base of Reliability Centered Maintenance. They concluded that cost benefit can be achieved by implementing the strategic maintenance on the basis of Reliability Centered Maintenance. Khobare et al. [5] developed the fault tree model for analysis of reliability of programmable and integrated comparator system of a microcomputer circuit. They modeled the programmable and integrated comparator system. Kolowrocki et al. [6] used the semi-Markov process for generalized modeling and evaluation of reliability of a complex port oil transportation system under variable operating conditions. Kumar et al. [7] presented the study concerned with deciding the priorities for maintenance of a repairable system at thermal plant. Markov technique was applied for availability analysis of the system and on the basis of this analysis. Sharma et al. [8] presented performance modelling and availability analysis using Markov birth-death process. Tewari et al. [9] developed a maintenance strategy for management for a sugar plant for enhancement of performance of crystallization unit. Genetic algorithm technique was used to optimize the system performance. Kumar et al. [10] developed semi-Markov process based model for mechanical systems and solved the model in two stages using analytical method for analyzing the availability in steady state. Genetic algorithm is then used to decide the best policy for centre based maintenance. Aggarwal et al. [11] used the fuzzy concept of reliability in a sugar plant for analyzing the availability of crystallization system. By using the mnemonic rule, mathematical model was prepared and then solved using Runge Kutta fourth order method.

In the present study, an attempt has been made to determine the maintenance priorities of a repairable crushing unit of a sugar plant on the basis of performance modeling and analysis of the unit using Markov process.

2. Unit description
The disintegrated cane is subjected to the Crushing Unit where it first passes through four sets of crushers. The subsequent sets of crushers perform the function of extracting the juice from bagasse soaked in water or imbibition fluid. Inter carriers are steel carriers which convey the bagasse from the release of one set of crusher to the feed side of next set of crusher successively. Juice strainers installed on the mills separate the bagasse particles drop from the crushers into the juice. The Juice collected under the crushers in troughs is guided into cylindrical tanks with the help of pumps. The description of crushing unit is as follows:

I. Subsystem B$_1$ : Four sets of crushers are there in series arrangement. These crushers perform the juice extraction function. Crushers squeeze the pulp of cane beneath extremely high pressure. The whole unit stops due to malfunctioning of any set of crusher.

II. Subsystem B$_2$ : Three number of inter carriers are there in series arrangement. The unit will not remain available for working after the failure of anyone of the inter carrier.

III. Subsystem B$_3$ : Four sets of pumps (two pumps in each set of which one is functional while the other in the cold standby mode). Standby pump comes into action just after the failure of functional one and the failed pump is sent to maintenance section. The whole unit will stop working immediately after the failure of any two set of pumps simultaneously.
2.1. Assumptions
The assumptions considered for expanding the performance model are as:

1) Failure and Repair rates do not change with time and are independent in statistics.
2) Repaired component will also offer the similar performance as that of a new component, for specific duration.
3) Sufficient repair facilities ensure the instant start of repair just after the occurring of failure.
4) Failure or repair of a particular component pursues the exponential allocation.
5) Service incorporates repair as well as replacement of the components.
6) Working of the unit under reduced capacity is also possible.

2.2. Notations
The following notations are addressed for the purpose of Performance modeling of the unit:

| B1       | Operative state of the Crusher | Φ6                   | Rate of Failure of the Crusher |
|----------|--------------------------------|-----------------------|-------------------------------|
| B2       | Operative state of the Inter Carrier | Φ7                   | Rate of Failure of the Inter Carrier |
| B3       | Operative state of the Pump | Φ8                   | Rate of Failure of the Pump |
| b1       | Failed state of Crusher subsystem | µ6                   | Rate of Repair rate of the Crusher |
| b2       | Failed state of Inter Carrier subsystem | µ7                   | Rate of Repair rate of the Inter Carrier |
| b3       | Failed state of Pump subsystem | µ8                   | Rate of Repair of the Pump |
| P0, P3   | Probabilities that the Unit is working | Working state of the Crushing Unit |
| P1, P2, P4, P5, P6 | Probabilities that the Unit is failed. | Failed state of the Crushing Unit |

Transition diagram has been presented by figure 2, for the crushing unit.
Seven possible states of the unit are described as:
State 0 and state 3 – Unit is working with full capacity
1, 2, 4, 5 & 6 state indicates the failure mode of crushing unit due to the reason of malfunctioning of any of the subsystem.

![Figure 2. Transition Diagram for the Crushing Unit](image)

### 3. Performance Modeling

Performance modeling has been executed by taking into account the probabilistic considerations. Markov birth-death process is used to expand differential equations connected with the transition diagram (figure 2). Steady state availability of the crushing unit is then computed after solving these equations. Different probability considerations proffer subsequent the equations associated to the unit under study, which are as follows:

1. \[ P_0'(t) + \Phi_6 P_0(t) + \Phi_7 P_0(t) + \Phi_8 P_0(t) = \mu_6 P_1(t) + \mu_7 P_2(t) + \mu_8 P_3(t) \]  
2. \[ P_1'(t) + \mu_6 P_1(t) = \Phi_6 P_0(t) \]  
3. \[ P_2'(t) + \mu_7 P_2(t) = \Phi_7 P_0(t) \]  
4. \[ P_3'(t) + \Phi_6 P_3(t) + \Phi_7 P_3(t) + \Phi_8 P_3(t) + \mu_6 P_3(t) = \mu_6 P_4(t) + \mu_7 P_5(t) + \mu_8 P_4(t) + \Phi_8 P_0(t) \]  
5. \[ P_4'(t) + \mu_6 P_4(t) = \Phi_6 P_3(t) \]  
6. \[ P_5'(t) + \mu_7 P_5(t) = \Phi_7 P_3(t) \]  
7. \[ P_6'(t) + \mu_8 P_6(t) = \Phi_8 P_3(t) \]

With initial conditions at time \( t = 0 \)

\[ P_i(t) = 1 \text{ for } i = 0, \]
\[ P_i(t) = 0 \text{ for } i \neq 0 \]

#### 3.1 Steady State Behaviour
It becomes vital for any process industry that all its operating units remain available for processing for stretched hours. For this reason, analysis of behaviour of the unit under steady state has been executed. Now, $P' = 0$ as $t \to \infty$. This gives the limiting probabilities through below equations (1) to (7):

\[ \Phi_6 + \Phi_7 + \Phi_8 \] $P_0 = \mu_6 P_1 + \mu_7 P_2 + \mu_8 P_3 \quad (8) \\
\mu_6 P_1 = \Phi_6 P_0 \quad (9) \\
\mu_7 P_2 = \Phi_7 P_0 \quad (10) \\
\mu_8 P_6 = \Phi_8 P_3 \quad (11)

Recursive solution of the above equations imparts:

\[ P_1 = G_6 P_0 \quad (12) \]
\[ P_4 = G_6 G_8 P_0 \quad (13) \]
\[ P_2 = G_7 P_0 \quad (14) \]
\[ P_5 = G_7 G_8 P_0 \quad (15) \]
\[ P_3 = G_8 P_0 \quad (16) \]
\[ P_6 = G_8 G_8 P_0 \quad (17) \]

\[ G_i = \frac{\Phi_i}{\mu_i} \quad i = 1,2,3,4,5 \]

Use of Normalizing condition i.e. sum of all the state probabilities is equal to one $[\sum_{i=0}^{6} P_i = 1]$, bestows the solution as follows:

\[ P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 = 1 \quad (18) \]
\[ P_0 + G_6 P_0 + G_7 P_0 + G_8 P_0 + G_6 G_8 P_0 + G_7 G_8 P_0 + G_8 G_8 P_0 = 1 \quad (19) \]
\[ P_0 [1 + G_6 + G_7 + G_8 + G_6 G_8 + G_7 G_8 + G_8 G_8] = 1 \quad (20) \]
\[ P_0 = 1/[1 + G_6 + G_7 + G_8 + G_6 G_8 + G_7 G_8 + G_8 G_8] \quad (21) \]

Now, on summing up the probabilities of all the full working state probabilities, evaluation of steady state availability ($AV_2$) of the crushing unit can be done:

\[ AV_2 = P_0 + P_3 \quad (22) \]
\[ AV_2 = P_0 + G_8 P_0 \quad (23) \]
\[ AV_2 = P_0 [1 + G_8] \quad (24) \]
\[ AV_2 = [1 + G_8] /[1 + G_6 + G_7 + G_8 + G_6 G_8 + G_7 G_8 + G_8 G_8] \quad (25) \]
\[ Availability = [1 + G_8] /[1 + G_6 + G_7 + G_8 + G_6 G_8 + G_7 G_8 + G_8 G_8] \quad (26) \]

4. Performance analysis

Availability is actually the quantification of the performance level of the concerned unit. Log books of maintenance department are referred for getting the rates of failure as well as rates of repair of the concerned subsystems. The developed decision matrices help in the analysis of different levels of performances using different failure and repair rate combinations. Decision matrices of various subsystems of the unit are represented by the tables 1, 2 and 3. Decision making for maintenance related tasks can be done on the basis of these decision matrices. After knowing the level of criticality of all the subsystems, the most beneficial blend of failure rate and repair rate may easily be taken into account.
Table 2. Decision Matrix for ‘Crusher’

| $\Phi_6$ | $\mu_6$ | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | Constant Parameters |
|----------|---------|------|------|------|------|------|---------------------|
| 0.005    | 0.8627  | 0.9016 | 0.9154 | 0.9224 | 0.9267 | $\Phi_7=0.005,$ $\mu_7=0.10$ |
| 0.010    | 0.7942  | 0.8627 | 0.8883 | 0.9016 | 0.9098 | $\Phi_8=0.01,$ $\mu_8=0.10$ |
| 0.015    | 0.7358  | 0.8271 | 0.8627 | 0.8818 | 0.8936 |           |
| 0.020    | 0.6854  | 0.7942 | 0.8386 | 0.8627 | 0.8779 |           |
| 0.025    | 0.6414  | 0.7639 | 0.8158 | 0.8445 | 0.8627 |           |

Figure 3. Trend of unit availability with respect to failure rate and repair rate of crusher

Table 3. Decision Matrix for ‘Inter Carrier’

| $\Phi_7$ | $\mu_7$ | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | Constant Parameters |
|----------|---------|------|------|------|------|------|---------------------|
| 0.005    | 0.9154  | 0.9296 | 0.9368 | 0.9412 | 0.9442 | $\Phi_6=0.005,$ $\mu_6=0.15$ |
| 0.010    | 0.8753  | 0.9016 | 0.9154 | 0.9239 | 0.9296 | $\Phi_6=0.01,$ $\mu_6=0.10$ |
| 0.015    | 0.8386  | 0.8753 | 0.8949 | 0.9071 | 0.9154 |           |
| 0.020    | 0.8049  | 0.8505 | 0.8753 | 0.8909 | 0.9016 |           |
| 0.025    | 0.7737  | 0.8271 | 0.8566 | 0.8753 | 0.8883 |           |

Figure 4. Trend of unit availability with respect to failure rate and repair rate of intercarrier
Table 4. Decision Matrix for ‘Pump’

| Φ₈  | µ₈  | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | Constant Parameters |
|-----|-----|------|------|------|------|------|---------------------|
| 0.01| 0.9154 | 0.9195 | 0.9211 | 0.9218 | 0.9222 | Φ₆ = 0.005, µ₆ = 0.15 |
| 0.02| 0.8955 | 0.9099 | 0.9154 | 0.9181 | 0.9195 | Φ₇ = 0.005, µ₇ = 0.10 |
| 0.03| 0.8676 | 0.8955 | 0.9067 | 0.9123 | 0.9154 |                       |
| 0.04| 0.8350 | 0.8776 | 0.8955 | 0.9046 | 0.9099 |                       |
| 0.05| 0.8000 | 0.8571 | 0.8824 | 0.8955 | 0.9032 |                       |

Figure 5. Trend of unit availability with failure rate and repair rate of pump subsystem

5. Results and discussion

Decision matrices present the variation of unit availability with change in failure rates as well as repair rates of various subsystems. The effect of failure and repair rates on the overall performance of the unit, in terms of availability, can be clearly seen through these decision matrices and respective figures.

It is revealed from Table 2 and respective figure 3 that with the increase of failure rate of crusher (Φ₆) from 0.005 to 0.025 (i.e. one time in 200 hrs to one time in 40 hrs), there is a drastic decrease in unit availability by 22%. Also, with the increase of repair rate (µ₆) from 0.05 to 0.25 (i.e. one time in 4 hrs to one time in 40 hrs), the unit availability appreciably increases by 6%.

It is revealed from Table 3 and respective figure 4 that with the increase of rate of failure of the inter carrier subsystem (Φ₇) from 0.005 to 0.025 (i.e. one time in 200 hrs to one time in 40 hrs), there is an extensive decrease in the availability by 14%. Also, with the increase of repair rate (µ₇) from 0.10 to 0.30 (i.e. one time in 10 hrs to one time in 3 hrs), the unit availability noticeably increases by 3%.

It is revealed from Table 4 and respective figure 5 that with the increase of failure rate of pump subsystem (Φ₈) from 0.01 to 0.05 (i.e. one time in 100 hrs to one time in 20 hrs), there is a large decrease in the availability by 11%. Also, with the increase of repair rate (µ₈) from 0.10 to 0.30 (i.e. one time in 10 hrs to one time in 3 hrs), the unit availability merely increases by 1%.

It is apparent from the above results that rates of failure as well as repair of the crusher subsystem have maximum effect on overall availability of crushing unit. Also, the rates of failure and rate of repair of pump subsystem have minimum effect on overall availability of crushing unit. The repair and maintenance of crusher subsystem is the most imperative concern for the management of sugar plant. Therefore, from the maintenance perspective, the crusher subsystem should be kept on top priority while taking the maintenance decisions. The maintenance priorities determined on the basis of above study are presented in the table 5.
6. Conclusions

The Performance modeling of a repairable crushing unit has been performed thereby analyzing performance of unit in the terms of availability. These levels of availabilities for various blends rates of failure as well as repair are presented in decision matrices of respective subsystems. Relationship between various failure and repair rates can also be understood from these decision matrices.

On the basis of these decision matrices, the maintenance priorities have been decided for crushing unit of a sugar plant (refer table 5).

Further, these decision matrices are helpful in determination of maintenance strategies for the concerned unit. This will ensure maximum availability level for the crushing unit.

This will finally lead to overall performance enhancement and hence maximum profitability of the sugar plant, which is the ultimate goal of any industrial enterprise.

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References

[1] Blake J T and Trivedi K S 1989 IEEE Transactions on Reliability 38 111-20
[2] Gupta S, Tewari P C and Sharma A K 2009 Journal of Industrial and Systems Engineering 3 85-96
[3] Hokstad P, Langseth H, Lindqvist B H and Vatn J 2005 International Journal of Performability Engineering 1 51-64
[4] Jaffer M A, Udaipappan M, Taisum T K, and Srinivasan S 2013 International Journal of Performability Engineering 9 445-54
[5] Khobare, S K, Shrikhande, S V, Chandra U and Govindarajan G 1998 Reliability Engineering and System Safety 59 253-58
[6] Kolowrocki K and Soszynska, J 2010 International Journal of Performability Engineering 6 77-87
[7] Kumar P, Tewari P C and Khanduja D 2016 International Journal of Performability Engineering 12 561-572
[8] Sharma D, Kumar A, Kumar V and Modgil V 2017 International Journal of Mechanical and Production Engineering 5 1-5
[9] Tewari P C, Khanduja R and Gupta M 2012 Journal of Industrial Engineering International 8 1-9
[10] Kumar G, Jain V and Gandhi O P 2018 Journal of Industrial Engineering International 14 119-31
[11] Aggarwal A K, Kumar S, Jain V and Singh V 2017 Journal of Industrial Engineering International 13 47-58

Table 5. Maintenance Priority Level of Subsystems

| Subsystem  | Increase in Repair Rate | Increase in Availability | Maintenance Priority Level |
|------------|-------------------------|--------------------------|---------------------------|
| Crusher    | 0.05 - 0.25             | 6 %                      | I                         |
| Inter Carrier | 0.10 - 0.30              | 3 %                      | II                        |
| Pump       | 0.10 - 0.30             | 1 %                      | III                       |