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# Performance evaluation and availability analysis of ammonia synthesis unit in a fertilizer plant

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## Abstract

This paper discusses the performance evaluation and availability analysis of ammonia synthesis unit of a fertilizer plant. The fertilizer plant is a complex and repairable engineering system comprises of various units viz. shell gasification and carbon recovery, desulphurization, co-shift conversion, decarbonation, nitrogen wash and ammonia synthesis etc. One of the most important functionaries of a fertilizer plant is ammonia synthesis unit. This unit consists of five subunits arranged in series and parallel configurations. For the evaluation of performance and analysis of availability, a performance evaluating model has been developed with the help of mathematical formulation based on Markov Birth-Death process using probabilistic approach. The findings of this paper are therefore, considered to be useful for the analysis of availability and determination of the best possible maintenance strategies in a fertilizer plant concerned.

**Keywords:** Steady state availability; Maintenance strategies; Performance evaluation

## 1. Introduction

During the last three decades reliability technology has been developed for use in various technological fields. The technology is mainly used in the development of electrical and electronics equipments. The technology has also been used in a number of industrial and transportation problems. A detailed bibliography is contained in Dhillon and Singh [2] and Srinath [13].This paper discusses an industrial problem concerned with a fertilizer plant. Although there are many functional units in a fertilizer plant viz. shell gasification and carbon recovery, desulphurization, co-shift conversion, decarbonation, nitrogen wash and ammonia synthesis etc., we consider ammonia synthesis unit which is most important functionaries of a fertilizer plant [4,5]. For efficient functioning, it is essential that various units of the plant remain in upstate as far as possible. However, during operation they are liable to fail in a random fashion. The failed elements can however be inducted back into service after repairs/replacements. The rate of failure of the components in the system depends upon the operating conditions and repair policy used [10].

A repairable system is characterized by a large number of interconnected components with their own failure behavior and repair time distributions. System availability in such a case is a complex function of failure and repair time distributions of individual components within the system [6]. This paper discusses the performance evaluation and availability analysis of ammonia synthesis unit in a medium sized fertilizer plant.

## 2. Ammonia Synthesis Unit

In this process the gas mixture available from decarbonation unit is first washed and then sprayed in

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the nitrogen wash column, where CO, Ar and $CH_4$ gases are liquefied and removed as tail gases. Then nitrogen in the gas mixture to make the $H_2$: $N_2$ ratio as 3:1.The gas mixture available at 37 kg/cm$^2$ and 391$^0$C, is raised to 231kg/cm$^2$ and 41$^0$C (using centrifugal type ammonia synthesis compressor) and then further raised to134$^0$C (using a hot heat exchanger). Then it enters the top of an ammonia converter (a radial flow type equipment consisting of a pressure shell and a basket) where reaction of $H_2$ and $N_2$ takes place producing ammonia gas and is collected at the bottom. This gas is cooled to 10$^0$C (using a cold heat exchanger and ammonia cold condenser), then it is collected in ammonia tank and supplied to the urea plant [7].

### 2.1. Description of ammonia synthesis unit

It comprises of five subunits as arranged in series:

- Subunit (A) consists of three centrifugal compressors in series. Failure of any one causes complete failure of the unit.
- Subunit (B) consists of hot heat exchanger and ammonia converter arranged in parallel. Each comprises of two working equipments (in parallel, used to increase the capacity of respective equipment). Failure of any one at a time only reduces the processing capacity. The complete failure is considered only when both equipments remain in failed state.
- Subunit (C) consists two heat exchangers one working and other in cold standby. Failure of any one will not affect the production since the standby equipment comes into operation. The complete unit failure occurs only when both equipments remain in failed state at a time.
- Subunit (D) consists of cold condenser and ammonia separator arranged in series. Failure of any one causes the complete failure of the unit.
- Subunit (E) consists of three-heat exchanger arranged in series. Failure of any are causes the complete failure of the unit.

### 2.2. Assumptions

The assumptions used in developing the probabilistic model are:

1) Failure/repair rates are constant over time and statistically independent [8].
2) A repaired unit as good as new, performance wise, for a specified duration.
3) Sufficient repair facilities are provided [13].
4) Standby units are of the same nature as that of active units [3].
5) System failure/repair follows the exponential distribution.
6) Service includes repair and/or replacement [3].
7) System may work at reduced capacity [10].
8) There are no simultaneous failures [7,14].

The transition diagram [8] (Figure 1) of ammonia synthesis unit shows the various possible states, the system can acquire. Based on the transition diagram, a performance-evaluating model has been developed. The failures and repairs for this purpose have been modeled as birth and death process.

### 2.3. Notations

The notations used to represent the various states of the subunits and transition diagram of the ammonia synthesis unit in Figure 1, are as follows:

A,B,C,D,E: Denotes that the subunits are in full operating state.

Cs : Denotes that the subunit C is working on standby unit.

B1 : Denotes that the subunit B is working in reduced state.

a,b,c,d,e: Denotes that the subunits A, B, C, D, E are in failed state.

$P_0$ (t) : Probability of the unit working with full capacity at time‘t’.

$P_1$ (t) : Probability of the unit in cold standby state.

$P_2$ (t)-$P_3$ (t): Probability of the unit in reduced capacity state.

$P_4$ (t) -$P_{15}$ (t):Probability of the unit in failed state.

$\alpha_i$ i =1-5 : Mean failure rate in A, B, C, D, E.

$\beta_i$ i =1- 5 : Mean rate of repairs in A, B, C, D, E.

d/dt : Represents derivative w.r.t. time (t).

: Unit working at full capacity.

: Reduced capacity state.

: Failed state.

## 3. Performance Modeling

The performance modeling is an activity in which the performance of a system is characterized by a set of performance parameters (repair and failure rates) whose quantitative values are used to assess the system's availability. The failure and repair rates are statistically independent and these can be obtained with the help of history cards and maintenance sheets of various subunits of the ammonia synthesis unit available with maintenance personnel of the fertilizer plant. Modeling is done using simple probabilistic considerations and differential equations are developed by using birth-death process. These equations are solved for determining the steady state availability of ammonia synthesis unit [9]. Various probability considerations give the following differential equations associated with the ammonia synthesis unit:

$$\left(d/dt+\sum_{i=1}^{5}\alpha_i\right)P_0(t)=\beta_1P_4(t)+\beta_2P_3(t)$$
$$+\beta_3P_1(t)+\beta_4P_5(t)+\beta_5P_6(t) \qquad (1)$$

$$\left(d/dt+\sum_{i=1}^{5}\alpha_i+\beta_3\right)P_1(t)=\beta_1P_7(t)+\beta_2P_2(t)$$
$$+\sum_{i=3}^{5}\beta_iP_{7+i}(t)+\alpha_3P_0(t) \qquad (2)$$

$$\left(d/dt+\sum_{i=1}^{5}\alpha_i+\beta_3+\beta_2\right)P_2(t)=\sum_{i=1}^{5}\beta_iP_{10+i}(t)$$
$$+\alpha_2P_1(t)+\alpha_3P_3(t) \qquad (3)$$

$$\left(d/dt+\sum_{i=1}^{5}\alpha_i+\beta_2\right)P_3(t)=\sum_{i=1}^{2}\beta_iP_{15+i}(t)$$
$$+\sum_{j=4}^{5}\beta_jP_{14+j}(t)+\alpha_2P_0(t)+\beta_3P_2(t) \qquad (4)$$

$$(d/dt+\beta_m)P_i(t)=\alpha_mP_j(t) \qquad (5)$$

With the initial condition $P_0(0)=1$ and 0 otherwise. Since any fertilizer plant is a process industry where raw material is processed through various subunits continuously till the final product is obtained. Thus, the long run availability of the ammonia synthesis unit of a fertilizer plant is attained by putting derivative of all probability equal to zero as $d/dt=0$ at $t\to\infty$ into differential equations, one gets:

$$P_i=(\alpha_m/\beta_m)P_j \qquad (6)$$

where in equation (6); for

m=1: i = 4, j = 0; i =7, j=1; i =11, j=2; i =16, j =3

m = 2: i = 2, j =2; i =7, j =3

m = 3: i = 8, j =1; i =13, j =2

m = 4: i = 5, j = 0; i=9, j =1; i=14,j =2; i =18, j =3

m = 5:i=6, j=0; i =10, j =1; i =15,j =2; i =19, j =3

Now putting the values of probabilities from Equations (6) in Equations (1) to (4), and solving these equations recursively, we get the steady state probabilities:

$$(\alpha_3+\alpha_2)P_0=\beta_3P_1+\beta_2P_3$$

$$(\beta_3+\alpha_2)P_1=\alpha_3P_0+\beta_2P_2$$

$$(\beta_3+\beta_2)P_2=\alpha_2P_1+\alpha_3P_3$$

$$(\alpha_3+\beta_2)P_3=\beta_3P_2+\alpha_2P_0$$

Now using these values one can found the values of all state probabilities in terms of full working state probability:

$$P_2=pP_0$$

$$p=\left\{\frac{\alpha_3\alpha_2(\beta_2+\beta_3+\alpha_2+\alpha_3)}{(\beta_2+\beta_3)(\beta_2+\alpha_3)(\alpha_2+\beta_3)}\right\}$$
$$-\alpha_3\beta_3(\alpha_2+\beta_3)-\alpha_2\beta_2(\alpha_3+\beta_2)$$

$$P_3=\{(\alpha_3+\beta_2p)/(\alpha_2+\beta_3)\}P_0$$

$$P_1 = \{(\alpha_2 + \beta_2 p /(\alpha_3 + \beta_2))\}P_0$$

The probability of full working capacity, namely, $P_0$ is determined by using normalizing condition (i.e. sum of the probabilities of all working states, reduced capacity and failed states is equal to 1) [10]:

$$\sum_{i=0}^{19} Pi = 1 \quad \text{Hence } P_0 = N^{-1}$$

$$N = \{1 + p + (\alpha_3 + \beta_2 p)/(\alpha_2 + \beta_3) + (\alpha_2 + \beta_2 p)/(\alpha_3 + \beta_2)\}$$
$$\times \{1 + \alpha_1/\beta 1 + \alpha_4/\beta_4 + \alpha_5/\beta_5\}$$
$$+ \alpha_3/\beta_3 \{p + (\alpha_3 + \beta_2 p)/(\alpha_2 + \beta_3)\}$$
$$+ \alpha_2/\beta_2 \{(\alpha_2 + \beta_2 p)/(\alpha_2 + \beta_2)\}$$

Now, the steady state availability of ammonia synthesis unit may be obtained as summation of all working and reduced capacity state probabilities as

$$\text{Hence} \quad \text{Av.} = \sum_{i=0}^{3} Pi = P_0 + P_1 + P_2 + P_3$$

$$Av. = \begin{Bmatrix} 1 + p + (\alpha_3 + \beta_2 p)/(\alpha_2 + \beta_3) + \\ (\alpha_2 + \beta_2 p)/(\alpha_3 + \beta_2) \end{Bmatrix} N^{-1}$$

Therefore, availability of the system (Av.) represents the performance evaluating model of ammonia synthesis unit. It is used for analysis of availability and evaluating the performance of this operating unit of a fertilizer plant. This model has been confirmed with the help of pay off matrix given in Table 1 and respective graphs, showing the effect of failure and repair rate of various subunits on the performance of ammonia synthesis unit, as given in Figures 2 to 6.

## 4. Performance evaluation

The availability or performance of ammonia synthesis unit in a fertilizer plant is mainly affected by the failure and repair rates of each subsystem. The failure rates of various subunits are assumed to follow exponential distribution for the simplicity of performance evaluation and availability analysis. These system parameters ensure the high availability of the ammonia synthesis unit. This performance evaluating model includes all possible states of nature, that is, future events $(\alpha_i)$ and the identification of all the courses of action, that is, repair priorities $(\beta_i)$. This model is used to implement the maintenance policies for ammonia synthesis unit in fertilizer plant. The various availability levels may be computed for different combinations of failure and repair rates / priorities. On the basis of analysis, one may select the best possible combination $(\alpha_i, \beta_i)$, that is, optimal maintenance strategies.

## 5. Availability analysis

Table 1 and Figure 2 show the effect of failure and repair rates of centrifugal compressor upon the availability of ammonia synthesis unit as failure rates of centrifugal compressor $(\alpha_1)$ increases from 0.001(once in 1000 hrs) to 0.01(once in 100 hrs), the system availability decreases considerably 34 %. Similarly as the repair rate $(\beta_1)$ increases from 0.01 (once in 100 hrs) to 0.04 (once in 25 hrs), the system availability increases only by 6%.

Table 1 and Figure 3 depict the effect of failure and repair rates of hot heat exchanger and ammonia converter etc on the availability of ammonia synthesis as failure rate of hot heat exchanger and ammonia converter $(\alpha_2)$ increases from 0.001(once in 1000 hrs) to 0.01(once in 100 hrs) ,the system availability decreases marginally by 2 %. Similarly as the repair rate $(\beta_2)$ increases from 0.05 (once in 20 hrs) to 0.2 (once in 5 hrs), the system availability increases marginally by 0.04 %.

Table 1 and figure 4 highlight the effect of failure and repair rates of cold heat exchanger on the availability of ammonia synthesis unit as failure rate of cold heat exchanger $(\alpha_3)$ increases from 0.001(once in 1000 hrs) to 0.01(once in 100 hrs), the system availability decreases, marginally by 1 %. Similarly as the repair rate $(\beta_3)$ increases from 0.1 (once in 10 hrs) to 0.4 (once in 2.5 hrs), the system availability increases marginally by 0.03 % only.

Table 1 and Figure 5 explain the effect of failure and repair rates of condenser and ammonia separator on the availability of ammonia synthesis unit as failure rate of condenser and ammonia separator $(\alpha_4)$ increases from 0.001(once in 1000 hrs) to 0.004 (once in 250 hrs), the system availability decreases, considerably by 12%. Similarly as the repair rate $(\beta_4)$ increases from 0.05 (once in 20 hrs) to 0.2 (once in 5 hrs), the system availability increases only by 1 % only.

**Table 1.** Pay off matrix for the subunits of ammonia synthesis unit.

**Availability (Av.)** →

| $\alpha_1$ \ $\beta_1$ | **0.01** | **0.02** | **0.03** | **0.04** | Constant Values |
|---|---|---|---|---|---|
| **0.001** | 0.8132 | 0.8476 | 0.8598 | 0.866 | $\alpha_2 = 0.001$, $\alpha_3 = 0.005$, |
| **0.002** | 0.752 | 0.8132 | 0.8358 | 0.8476 | $\alpha_4 = 0.001$, $\alpha_5 = 0.001$, |
| **0.005** | 0.6135 | 0.7248 | 0.7714 | 0.797 | $\beta_2 = 0.05$, $\beta_3 = 0.2$, |
| **0.01** | 0.4695 | 0.6136 | 0.6835 | 0.7248 | $\beta_4 = 0.05$, $\beta_5 = 0.01$ |
| $\alpha_2$ \ $\beta_2$ | **0.05** | **0.1** | **0.15** | **0.2** | Constant Values |
| **0.001** | 0.8189 | 0.8191 | 0.8192 | 0.8193 | $\alpha_1 = 0.001$, $\alpha_3 = 0.005$, |
| **0.002** | 0.8182 | 0.8189 | 0.8191 | 0.8192 | $\alpha_4 = 0.001$, $\alpha_5 = 0.001$, |
| **0.005** | 0.8132 | 0.8176 | 0.8185 | 0.8188 | $\beta_1 = 0.01$, $\beta_3 = 0.2$, |
| **0.01** | 0.7975 | 0.8132 | 0.8164 | 0.8177 | $\beta_4 = 0.05$, $\beta_5 = 0.01$ |
| $\alpha_3$ \ $\beta_3$ | **0.1** | **0.2** | **0.3** | **0.4** | Constant Values |
| **0.001** | 0.8766 | 0.8767 | 0.8768 | 0.8769 | $\alpha_1 = 0.001$, $\alpha_2 = 0.005$, |
| **0.002** | 0.8764 | 0.8766 | 0.8767 | 0.8768 | $\alpha_4 = 0.001$, $\alpha_5 = 0.002$, |
| **0.005** | 0.8749 | 0.8762 | 0.8765 | 0.8766 | $\beta_1 = 0.01$, $\beta_2 = 0.2$, |
| **0.01** | 0.8699 | 0.8748 | 0.8758 | 0.8762 | $\beta_4 = 0.05$, $\beta_5 = 0.02$ |
| $\alpha_4$ \ $\beta_4$ | **0.05** | **0.1** | **0.15** | **0.2** | Constant Values |
| **0.001** | 0.8764 | 0.8842 | 0.8868 | 0.8881 | $\alpha_1 = 0.001$, $\alpha_2 = 0.005$, |
| **0.002** | 0.8613 | 0.8764 | 0.8816 | 0.8842 | $\alpha_3 = 0.002$, $\alpha_5 = 0.002$, |
| **0.003** | 0.8190 | 0.8539 | 0.8663 | 0.8726 | $\beta_1 = 0.01$, $\beta_2 = 0.2$, |
| **0.004** | 0.7570 | 0.8190 | 0.8419 | 0.8539 | $\beta_3 = 0.1$, $\beta_5 = 0.02$ |
| $\alpha_5$ \ $\beta_5$ | **0.01** | **0.02** | **0.03** | **0.04** | Constant Values |
| **0.001** | 0.8764 | 0.9166 | 0.9308 | 0.9381 | $\alpha_1 = 0.001$, $\alpha_2 = 0.005$, |
| **0.002** | 0.8058 | 0.8764 | 0.9028 | 0.9166 | $\alpha_3 = 0.002$, $\alpha_4 = 0.001$, |
| **0.003** | 0.7457 | 0.8396 | 0.8764 | 0.8960 | $\beta_1 = 0.01$, $\beta_2 = 0.2$, |
| **0.004** | 0.6939 | 0.8058 | 0.8515 | 0.8764 | $\beta_3 = 0.1$, $\beta_4 = 0.05$ |

**Table 2.** Optimum values of failure and repair rates of subunits of ammonia synthesis unit.

| Sr. No. | Failure Rates $(\alpha_i)$ | Repair Rates $(\beta_i)$ | Maximum Availability Level |
|---|---|---|---|
| 1. | $\alpha_1 = 0.001$ | $\beta_1 = 0.04$ | 87 % |
| 2. | $\alpha_2 = 0.001$ | $\beta_2 = 0.2$ | 82 % |
| 3. | $\alpha_3 = 0.001$ | $\beta_3 = 0.4$ | 88 % |
| 4 | $\alpha_4 = 0.001$ | $\beta_4 = 0.2$ | 89 % |
| 5. | $\alpha_5 = 0.001$ | $\beta_5 = 0.04$ | 94 % |

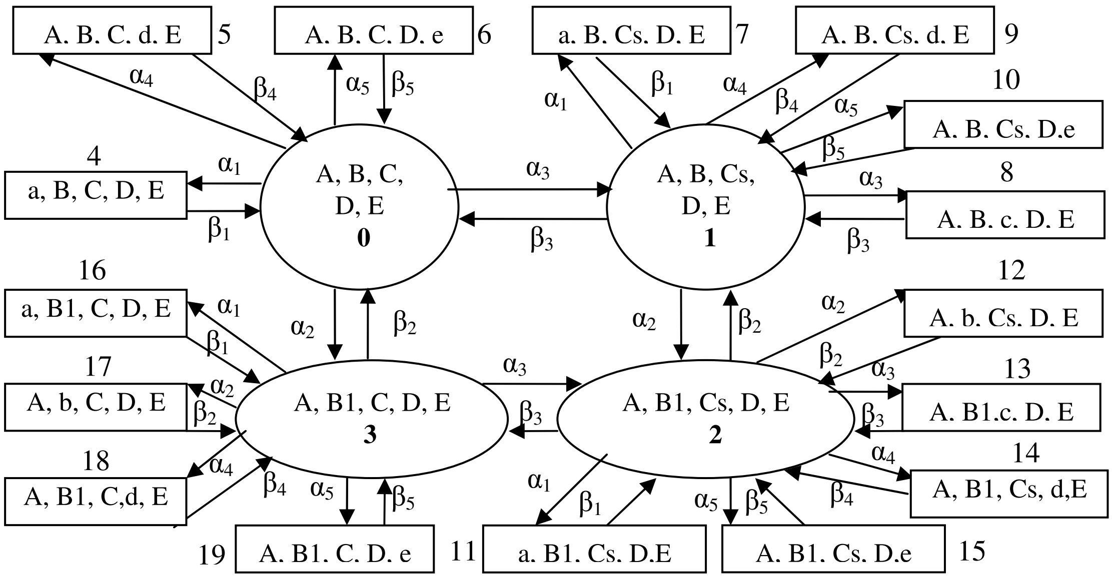


**Figure 1.** Transition diagram of the ammonia synthesis unit.

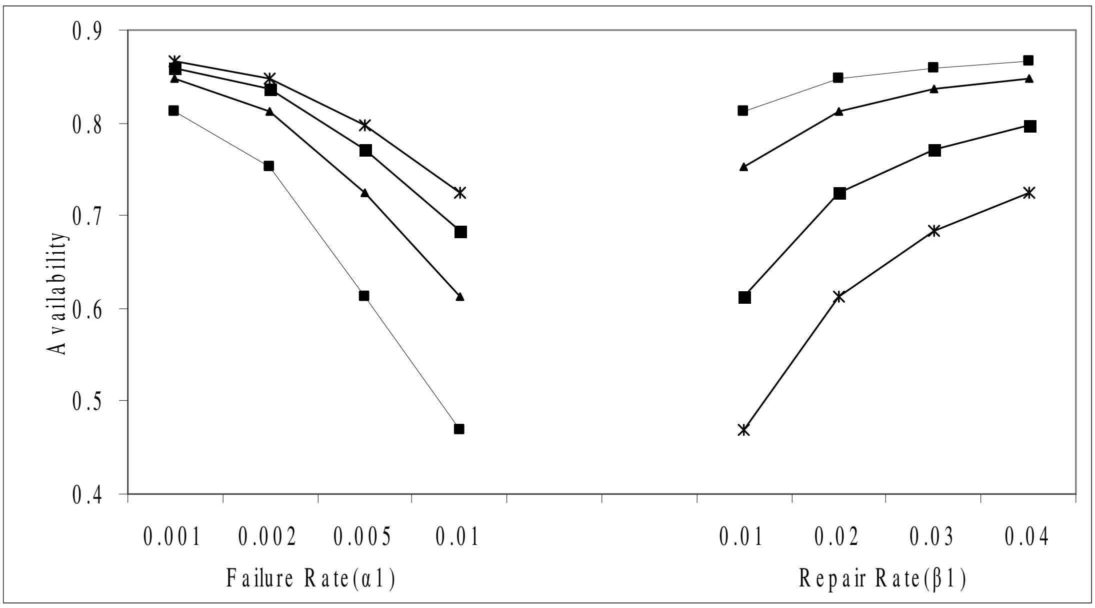


**Figure 2.** Effect of failure and repair rate of centrifugal compressor on availability of the ammonia synthesis unit.

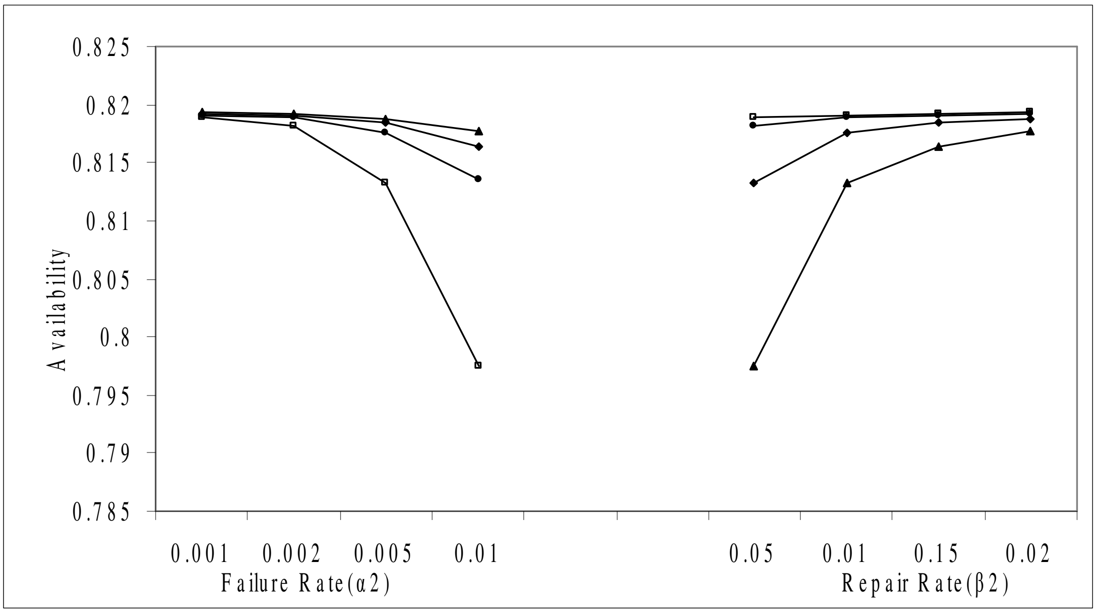


**Figure 3.** Effect of failure and repair rate of ammonia converter on availability of the ammonia synthesis unit.

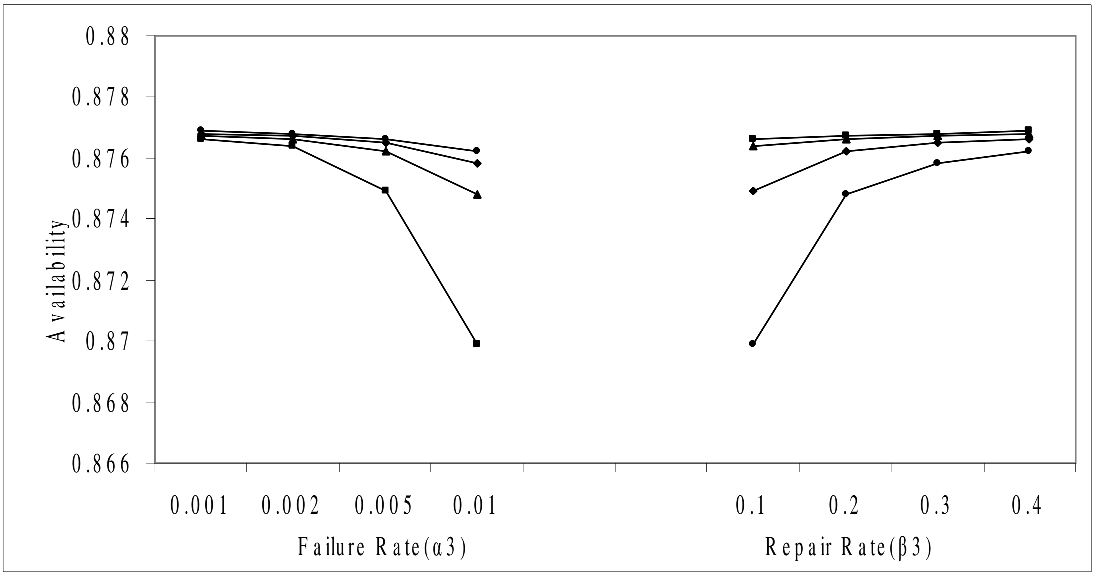


**Figure 4.** Effect of failure and repair rate of cold heat exchanger on availability of the ammonia synthesis unit.

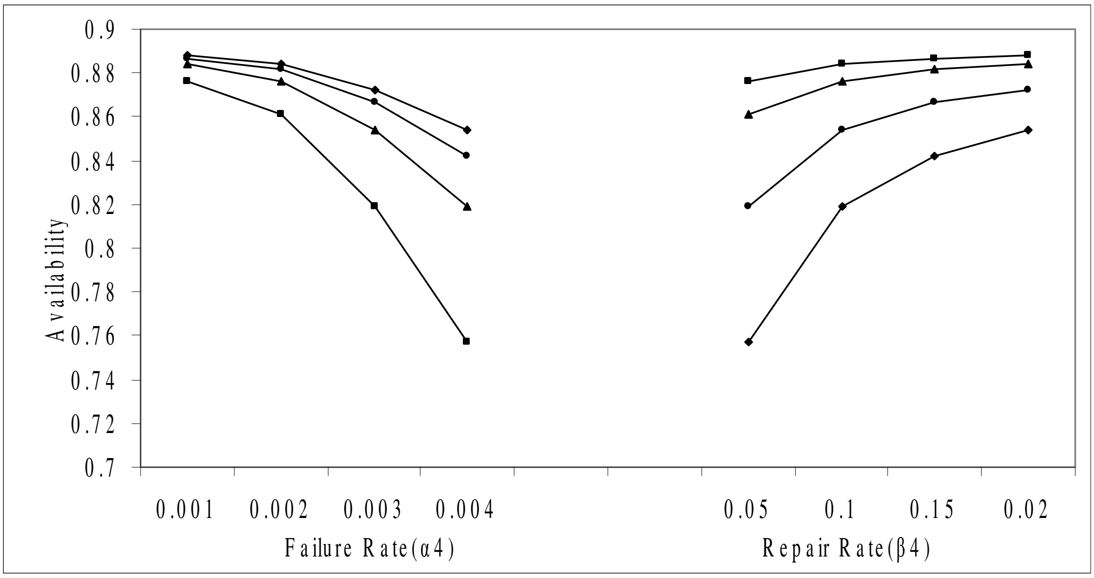


**Figure 5.** Effect of failure and repair rate of condenser and ammonia separator on availability of the ammonia synthesis unit**.**

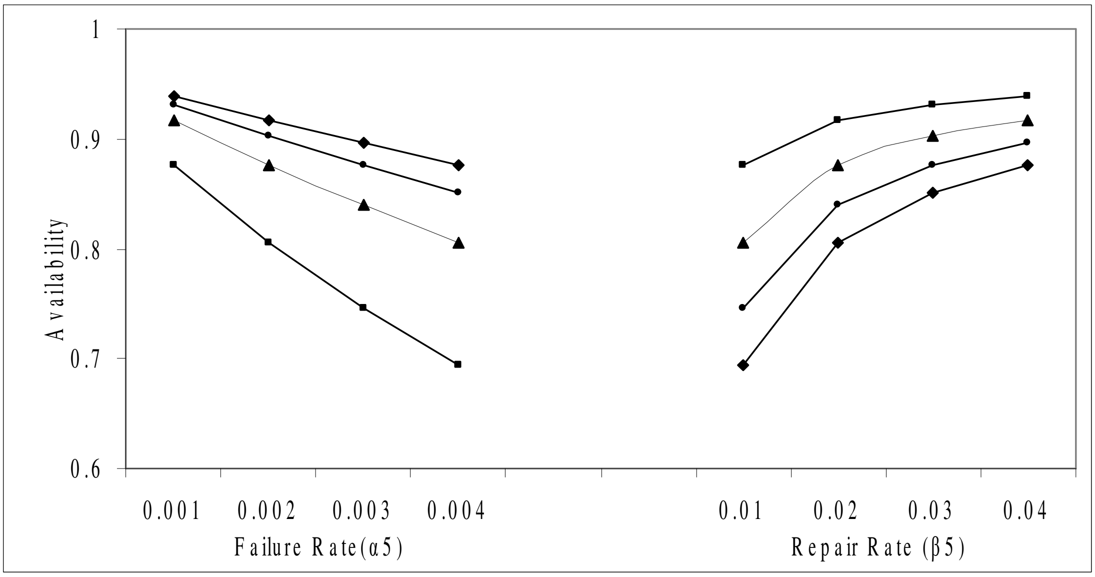


**Figure 6.** Effect of failure and repair rate of heat exchanger on availability of the ammonia synthesis unit.

Table 1 and Figure 6 show the effect of failure and repair rates of heat exchanger on the availability of ammonia synthesis unit as failure rate of heat exchanger $(\alpha_5)$ increases from 0.001(once in 1000 hrs) to 0.004 (once in 250 hrs), the system availability decreases by 18 %. Similarly as the repair rate $(\beta_5)$ increases from 0.01 (once in 100 hrs) to 0.04 (once in 25 hrs), the system availability increases by 6 %.

## 6. Conclusions

It can thus be concluded that this availability model is effectively used for the performance evaluation and hence the availability analysis of the ammonia synthesis unit of a fertilizer plant. It also shows the relationship among various failure and repair rates $(\alpha_{i,}\beta_i)$ for each subunit of ammonia synthesis unit of a fertilizer plant. It also provides the various availability levels ($A_{ii}$) for different combinations of failure and repair rates for each and every subunit. One may select the best possible combination of failure events and repair priorities for each subunit. It helps in determining the optimal maintenance strategies, which will ensure the maximum overall availability of the ammonia synthesis unit of a fertilizer plant. The optimum values of failure and repair rates for each subunit are given in Table 2 as shown below. The findings of this paper are discussed with the concerned fertilizer plant management. Such results are found highly beneficial to the plant management for the evaluation of performance and analysis of availability of ammonia synthesis unit and hence to decide about the maintenance priorities of various subunits of the unit concerned in a fertilizer plant.

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